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Soil ecosystem services, sustainability, valuation and management

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Abstract
Soils provide and regulate a large number of ecosystem services (ES) and play an important role in sustaining humanity. The benefits we receive from soils are directly or indirectly linked to clean air and water and food production, among others, and are key to poverty alleviation and climate change mitigation. These are some of the most important challenges for our society. The type, quantity or quality of soil ES depends on the specific environmental characteristics that will determine soil properties and functions. The valuation of soil ES depends on natural features and management type. Non-sustainable practices induce soil degradation/devaluation and a large number of disservices, while sustainable practices can maintain and improve soil ES. Overall, soil ES quality and quantity over the long-term will depend on how sustainably we manage our land.

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Introduction

Ecosystem services (ES) are goods obtained from ecosystems that benefit people's well-being [1]. Several classifications have been created to classify ES. The most frequently used are those developed by the Millennium Ecosystem Assessment (MA) [1], The Economics of Ecosystems and Biodiversity (TEEB) [2], Common Classification of Ecosystem Services (CICES) [3] and OpenNESS [4]. According to CICES [3], ES can be divided into provision (nutrition, materials, energy), regulation and maintenance (mediation of waste, toxics and other nuisances, mediation of flows, maintenance of physical, chemical and biological conditions) and cultural services (physical, intellectual, spiritual and symbolic interactions with biota, ecosystems, and land-/seascapes).

Soils are an important component of ecosystems and inter- and transdisciplinary approaches are needed to understand their dynamics. Soil is formed at the intersection of the lithosphere, biosphere, atmosphere and hydrosphere. It regulates the majority of ecosystem processes in landscapes and is home to a large proportion of earth's biodiversity, providing the physical foundation for numerous human activities. Since the first agricultural revolution, human impacts on soil became more negative [5,6]. However, anthropic impacts on soil go back as far as 13000 years ago [7]. Soils provide and regulate ES, and are part of human culture, being a crucial component of our existence since they are the basis for plants, raw material and food production. It is a conditionally renewable resource, thus, to maintain the quantity and quality of ES provided by soils, sustainable management is needed [8,9].

As a consequence of climate change and human pressure, soil ES are being drastically degraded, endangering food safety for coming generations. Climate change may diminish soil fertility by changing the soil-water-gas equilibrium and decreasing soil organic carbon. Moreover, soil is the largest terrestrial carbon sink, and if managed incorrectly, can be an important source of greenhouse gas emissions. Agricultural expansion, unsustainable practices, conversion of natural habitats in rural areas and urban sprawl are accelerating soil degradation at an alarming rate, with negative implications for soil value [10,11].

Soils determine the economic status of nations and therefore are an important natural capital [13]. Soil natural capital is defined by the capacity of soil to provide the ES required for a determined land use, assuming that sustainable practices are being used [14]. Previous works argued that soil components have

been overlooked as a vital resource, despite the fact that soil functions are key to ES [15,16]. Despite this, soil was neglected in the classification of ecosystem types for economical evaluation in TEEB [17]. Thus, it is critical that policy makers and land managers include soil within the frameworks that are used to evaluate ES [17].

Soil management has important implications for the quantity and quality of the ES provided, especially in agricultural and urban areas that are subject to high disturbances [18,19]. Intensive agricultural practices decrease soil biomass, biota and carbon, and increase soil compaction, acidification, erosion and salinization.

Soils in urban areas are sealed, intensively polluted, toxic to microbes and plants, and represent a threat to human health [20]. Similarly, in areas affected by mining activities, soils might not be capable of sustaining productive and functional ecosystems. Soil ES of provision, regulating and cultural value are specially threatened in areas that are intensively managed and more sustainable approaches are needed to reduce soil ES degradation. Restoring some of these degraded areas that are subject to severe disturbances is crucial to reinstate ES. The objective of this work is to review the a) importance of soil ES for sustainability, b) valuation and c) management impacts.

The importance of soil ecosystem services for sustainability

Soil functions, ES quality and quantity, and the sustainable development goals are intrinsically related [21,22]. Soil ES provisioning and regulating are crucial to poverty alleviation [23]. Basic human needs such as food, clean air and water are not possible without soil. The quantity and quality of the services provided are dependent on the parent material, relief (position, aspect and slope), biota, and climate. These characteristics largely determine soil properties and functions that are the basis for provisioning, regulating and cultural services (Fig. 1).

Soil natural capital and the services soil provides are crucial to sustainability. Provisioning services such as food, fiber, wood and raw materials would not be possible without the role of micro and macrofauna in critical soil functions [24]. These “ecosystem engineers” are involved in pedogenic processes and help develop key soil properties important for processes such as organic matter mineralization, nutrient cycling, structural development and primary production [25]. Soil provisioning ES are key for the sustainability of forest, agricultural and urban areas. Forests provide a wide range of services that depend directly or indirectly on soil such as food products (wild berries, mushrooms), wood, biomass, medicinal plants, pollination, oxygen and clean water. Forests also protect soils from degradation and improve their functions, such as carbon sequestration [26]. Services provided by forests are extremely important for human social, economic and health status, especially in developing countries, where people strongly depend on natural resources [27]. The value of soil ES increases when habitat conservation practices are employed [28].

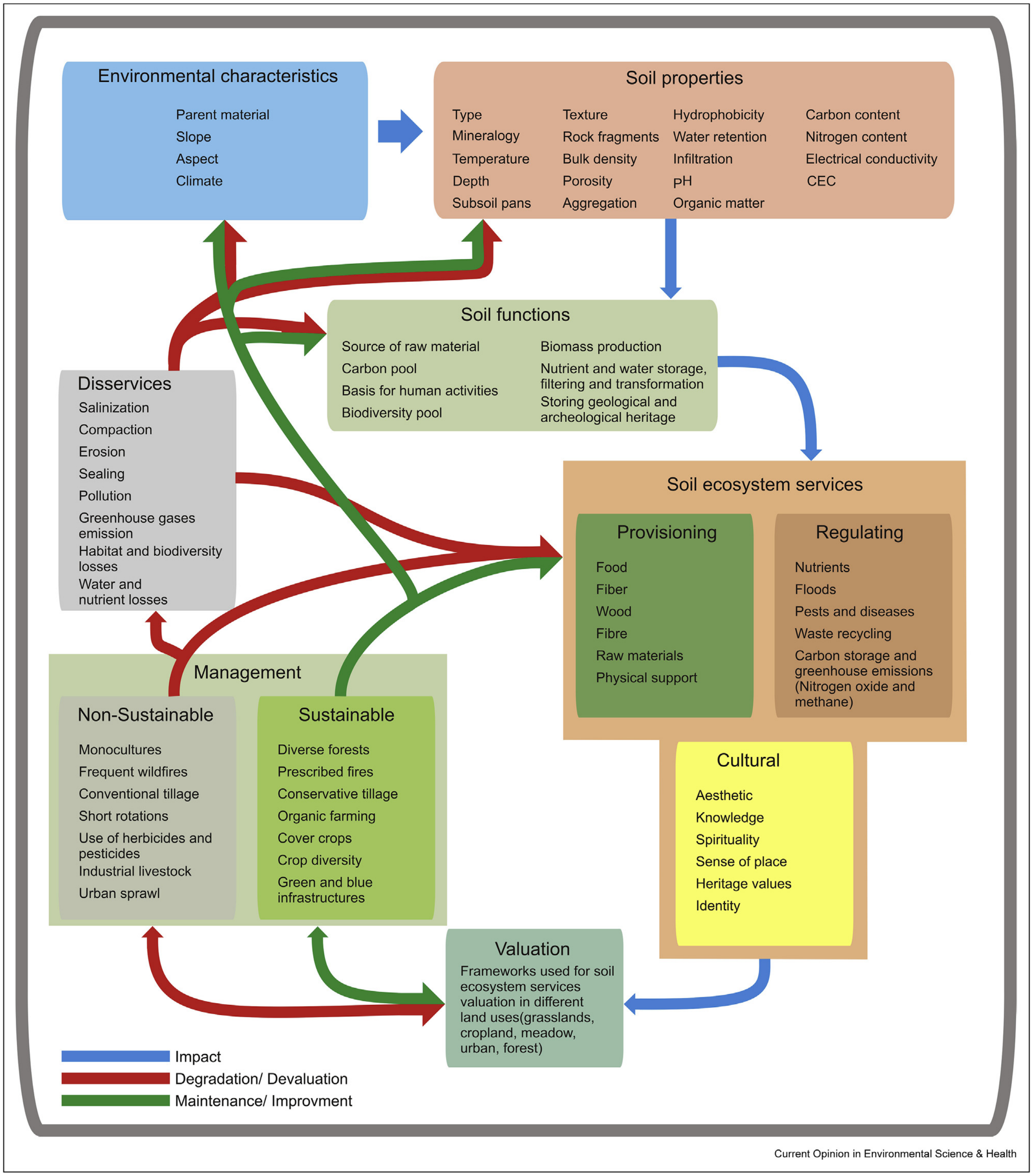
In agricultural areas, crop production is extremely dependent upon soil properties. Grain yield productivity is high at a soil pH between 6 and 8 [29] and increases with, organic matter [30], aggregation [31], biota [6], and decreases with soil compaction [32] and nutrient concentration. Soil productivity is strongly influenced by the type of management (we will developed it further). Heavily exploited soils can lead to land degradation, inducing poverty, migration and conflicts [33]. This is particularly relevant in developing countries, where the increasing population is inducing a high pressure on soil resources, and the social organization is more vulnerable to environmental changes [34].

Soils are the physical support for human settlements and urban development. Their mineralogical and physical properties determine road and buildings foundation requirements. One example of this are Vertisols, which are expansive soils rich in illite, vermiculite and smecite. They have a high plasticity and are responsible for higher costs of construction than earthquakes, floods, tornados, hurricanes and landslides combined. This poses a worldwide problem in places including Australia, the United Kingdom, China, India and the USA [35]. Another example is the thawing of permafrost in artic environments, which damages roads, buildings and other infrastructure [36]. In urban areas, soils are subjected to intense pressures, decreasing the quantity and quality of the ES they provide [11]. Despite these pressures, these soils are an important source of food production in urban gardens, contributing to long-term food security, city resilience, and enhancement of urban environments [19,37]. However, there are several concerns regarding soil contamination (especially near roads), quality of food, and impacts on human health [38].

Soils in forested areas provide important ES regulation such as nutrient maintenance; flood, erosion, pest, and disease control; waste recycling and carbon sequestration. This is especially important in forests that sustain high biodiversity. This decreases soil ES regulation capacity and affects the sustainability of the communities that depend on these areas [39].

Soil services regulation is crucial for effective productivity of agriculture areas. The capacity of soils to conserve carbon, water, and nutrients will determine their productivity and vulnerability to degradation.

Fig. 1



Soil ecosystem services and management framework.

Healthy soils have a higher capacity to retain carbon, water and nutrients, to regulate greenhouse gas emissions, and to maintain a higher resistance to pests and diseases [40]. The capacity of agricultural soils to regulate ES is decreasing as a consequence of an increase in the area covered by intensive plant production practices to feed livestock and humans. This abusive use reduces the long-term capacity of soils to regulate

services that are essential for the sustainability of ecosystems and communities [41].

Urban soil regulating services are degraded as a consequence of human impacts. Pseudo natural, vegetated engineered soils and soils from landfill sites have certain capacities to store water, control runoff and erosion, host biodiversity, contribute to air purification, and regulate global and local climate. However, in sealed soils, natural functions are strongly damaged and often destroyed. Regulating services have a low value in urban soils. These soils store water less water and have increased overland flow, nutrient transport and erosion when compared to similar, natural soils. In addition, degraded urban soils can contribute to the urban heat island effect [19]. Sealed soils in urban areas are responsible for an increased destruction capacity of flash floods, which induces high environmental (pollutant transport to water bodies), social (loss of life) and economic (infrastructure damage) costs in the affected areas [42].

Soils are part of human identity and an asset for cultural development. They were the basis of ancient civilizations that flourished (e.g Babilonia, Kanann, Rapa Nui) and contributed to their decline when intense use led to soil degradation. However, there are also examples of societies that engaged in long-term, sustainable soil practices and these societies were, in turn, sustainable over long time periods [7]. In this context, soil was largely responsible for the sustainability of these communities. During the historic and pre-industrial era, agricultural societies were more linked to soil than nowadays. These communities developed a deep knowledge – shaped for centuries – about soil functions, and forms of soil management according to their needs. One clear example is the Amazonian dark earth (*Terra preta de Indio*), which represents a shift in the relations between humans and nature, a cultural heritage and identity [43,44]. Soil is the basis for the different types of vegetation and traditional human land uses that shape landscape aesthetics and have inspired artists since pre-historic times. Moreover, soils are a climate and cultural archive [7] and are the support for our daily cultural and leisure activities [45].

Soil ecosystem services valuation

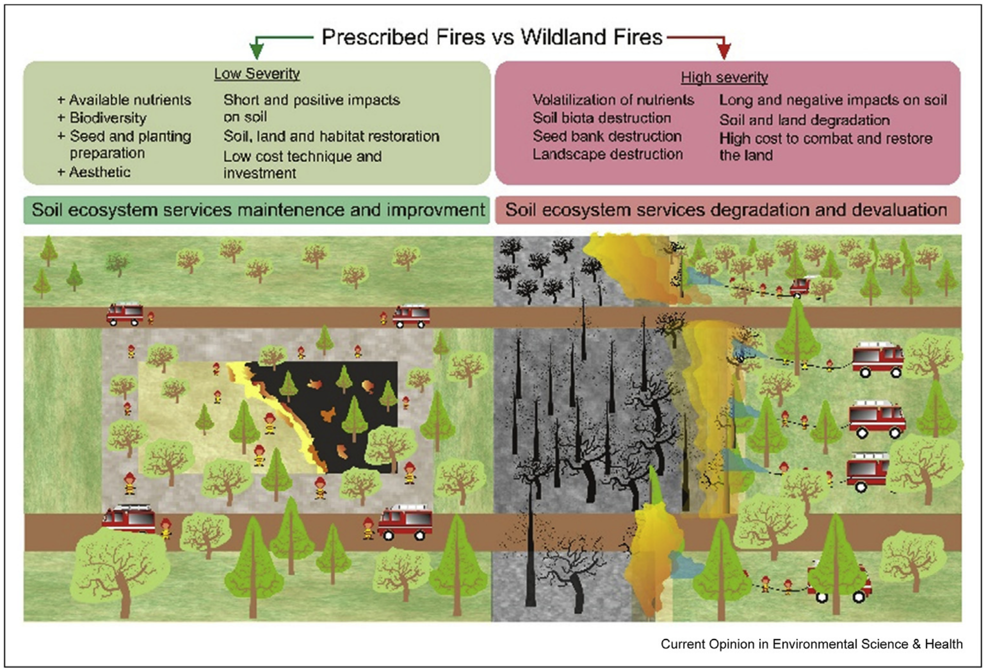
Soil ES value are dependent on what they can provide and how we manage them. The way we manage our land can lead soils to provide only short-term benefits that are not unsustainable, or benefits that are only noticeable over the long-term. Non-sustainable management can led to a devaluation and deterioration of the soil services provided by ecosystems, while sustainable management can maintain or improve these services (Fig. 1). Many studies on soil ES provisioning, regulating and cultural have been carried out in recent years [9,13,16]. Several frameworks for soil ES assessment have been designed for general soil services [14], but most of the evaluations were focused on agroecosystems [46,47]. These frameworks are used to improve our knowledge of the potential of agricultural practices to change agroecosystems and vice versa [48]. They should facilitate the incorporation of scientific knowledge, especially quantitatively, in ES assessment [49]. Soil ES assessment is dependent on market values, which can change between countries or regions where services have different values and over time [15].

Management impacts on soil ecosystem services

Soil ES valuation, devaluation, degradation, maintenance or improvement is strongly linked to land management (Fig. 1). Agroforests and the methods used during the tree plantation (e.g. heavy machinery) reduce soil ES, compared to a diverse natural forests. Monoculture for wood production is one of the main causes of wildfire frequency and severity increase, which have long term impacts on soil (Fig. 2). Despite the short-term profits from wood production, risks such as pests, diseases, and high wildfire risk make this type of management un-sustainable and create an important number of soil disservices (e.g. erosion, pollution of water bodies, greenhouse emissions, habitat and biodiversity losses and water and nutrient losses). In many ecosystems such as those in the Mediterranean region, fire is a natural phenomenon and plants are adapted to its effects. However, decreases in forest biodiversity, climate change and land abandonment are reducing the resilience of forests to fire [50]. Preventive strategies such as the application of prescribed fires are needed to manage forest biomass. Controlled burns can restore ecosystems and maintain or improve soil properties, if applied not frequently. The response of soil to prescribed fire depends on soil type, residence time, seasonality, frequency and the ecosystem affected, which should be considered when planning a prescribed fire [51]. Overall, prescribed fires have a lower impact on soil properties than wildfires and can be beneficial to soils (Fig. 2).

Non-sustainable land uses such as conventional tillage, short crop rotations, use of herbicides and pesticides and industrial livestock farms are well known for their negative effects on soil ES in agricultural areas (Fig. 1). Agricultural intensification and the use of pesticides and herbicides are some of the main causes of soil ES degradation and devaluation [52]. As a consequence of the high soil disturbances created by these practices, their application can lead to several disservices such as acidification, salinization, erosion, compaction, water and nutrient losses, greenhouse gas emissions and increased pollution. Degradation of soil ES have negative impacts on productivity, and the costs of restoration can be extremely high [10,15], leading to further degradation and devaluation. However, the effect of

Fig. 2

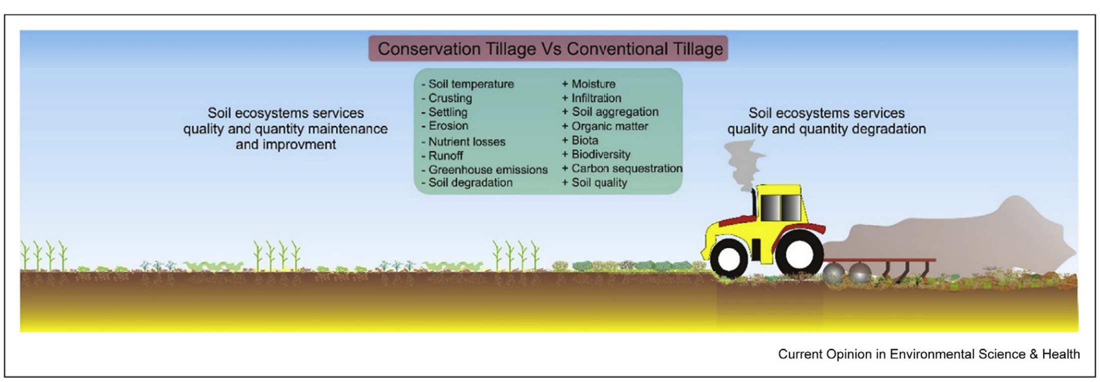


Prescribed fire vs wildland fires effect.

intensive agriculture goes beyond the environment and economy. The use of pesticides and herbicides has a negative impact on human health and increases our vulnerability to diseases such as cancer [53]. Sustainable management practices such as conservation tillage, organic farming, cover corps and crop diversity have long-term beneficial impacts on soil ES, maintaining or improving these services [48]. These sustainable practices are crucial to maintain soil biodiversity and provide important tangible and intangible economic values [54] (Fig. 3).

Urban sprawl is one of the main causes of soil degradation in urban and peri-urban areas, creating an important number of soil disservices such as sealing, pollution, habitat and biodiversity loss and water and nutrient losses (Fig. 1). The impacts of urban sprawl are very negative for society (e.g. stress increase, obesity) and the economy (e.g. increase in infrastructure and health expenses) [55]. New forms of urban planning based on natural solutions (e.g. green and blue infrastructure) are needed to reduce the impacts of human activities and cities on soil services, reducing

Fig. 3



Advantages of conservation tillage practices in relation to conventional tillage.

land consumption, the probability of chronic diseases, and associated costs [56].

Final remarks and conclusion

The approaches we follow to manage our lands can have critical effects on soil ES. On the one hand, non-sustainable uses can induce an important number of disservices, and also negatively affect the environmental characteristics of the land, soil properties, functions and services. On the other hand, sustainable approaches can maintain or improve these services. Non-sustainable practices accelerate the impacts of climate change on soil ES, while sustainable approaches help to mitigate its effects. Soil ES are directly linked with sustainability, and the damage or improvement induced by our activities will be reflected on our society and economy. Despite this understanding, more importance should be given to the soil system in the context of sustainable development. Likewise, more efforts should be made to create frameworks capable of analyzing soil services in non-agricultural areas. Ultimately, the maintenance and improvement of soil ES depends on how sustainable our practices are, which is a long-term key to achieve a balance between food security and sustainability.

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